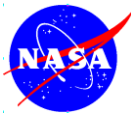


# **Tones encountered with a coannular nozzle and a method for their suppression**

**Khairul Zaman, James Bridges, Amy Fagan and Chris Miller**  
**NASA Glenn Research Center, Cleveland, OH 44135**

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## **Outline of talk:**

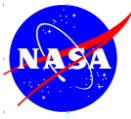
**Introduction**

**Experimental Facility**

**Experimental Results**

**Numerical Results**

**Summary**



## **Scope of the work:**

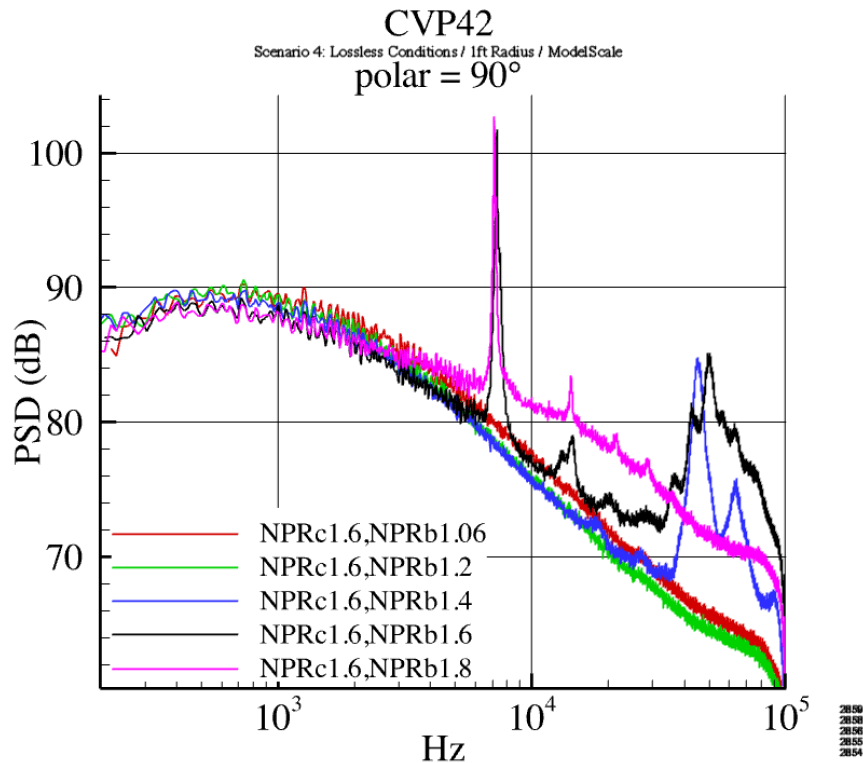
**Tones were encountered in larger-scale, multi-stream nozzle tests in the Aeroacoustics Propulsion Laboratory (AAPL).**

**An approximately half-scale model of a 2-stream nozzle was built to study the tones and find possible remedy.**

**This paper presents results from the model-scale experiment.**

**Results of a numerical study on duct acoustic modes corresponding to the tones are also presented.**

# Tone problem faced in the AAPL with a 2-stream nozzle



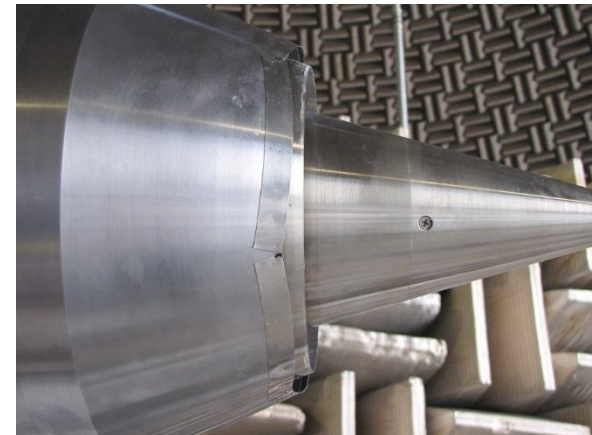
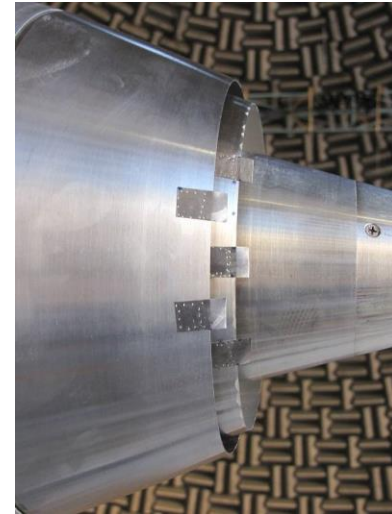
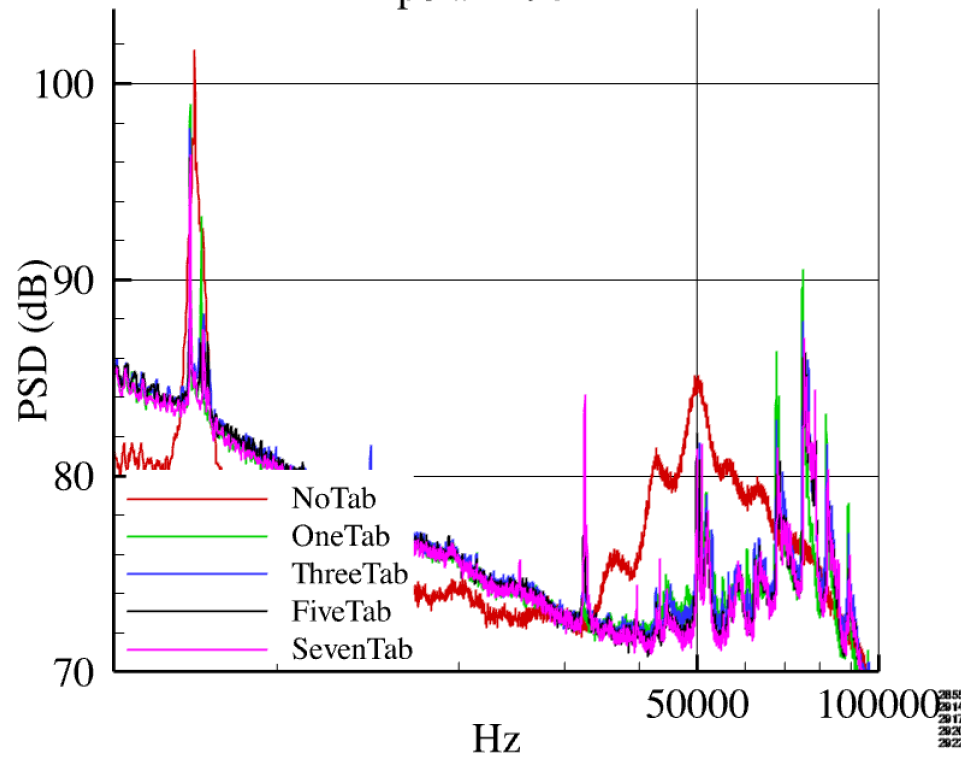
| NPRc  | NPRb  | NTRc  | NTRb  | Notes          |
|-------|-------|-------|-------|----------------|
| 1.595 | 1.620 | 1.819 | 1.254 | howling@7kHz   |
| 1.551 | 1.597 | 1.797 | 1.249 | howling@7kHz   |
| 1.510 | 1.576 | 1.776 | 1.244 | howling@7kHz   |
| 1.434 | 1.534 | 1.735 | 1.234 | howling@7kHz   |
| 1.354 | 1.488 | 1.688 | 1.222 | howling@7kHz   |
| 2     | 2     | 1.776 | 1.25  | howling@7kHz   |
| 2     | 1.8   | 1.776 | 1.25  | howling@7kHz   |
| 2     | 1.5   | 1.776 | 1.25  | rough stuff at |
| 2     | 1.064 | 1.776 | 1.25  | smooth         |
| 1.8   | 2.1   | 1.777 | 1.25  | howling@7kHz   |
| 1.8   | 1.8   | 1.777 | 1.25  | howling@7kHz   |
| 1.8   | 1.6   | 1.777 | 1.25  | howling@7kHz   |
| 1.8   | 1.4   | 1.777 | 1.25  | rough stuff at |
| 1.8   | 1.2   | 1.777 | 1.25  |                |
| 1.8   | 1.06  | 1.777 | 1.25  |                |
| 1.6   | 1.06  | 1.777 | 1.25  | smooth         |
| 1.6   | 1.2   | 1.777 | 1.25  | smooth         |
| 1.6   | 1.4   | 1.777 | 1.25  | rough stuff at |
| 1.6   | 1.6   | 1.777 | 1.25  | howling@7kHz   |
| 1.6   | 1.8   | 1.777 | 1.25  | howling@7kHz   |

## Remedies tried

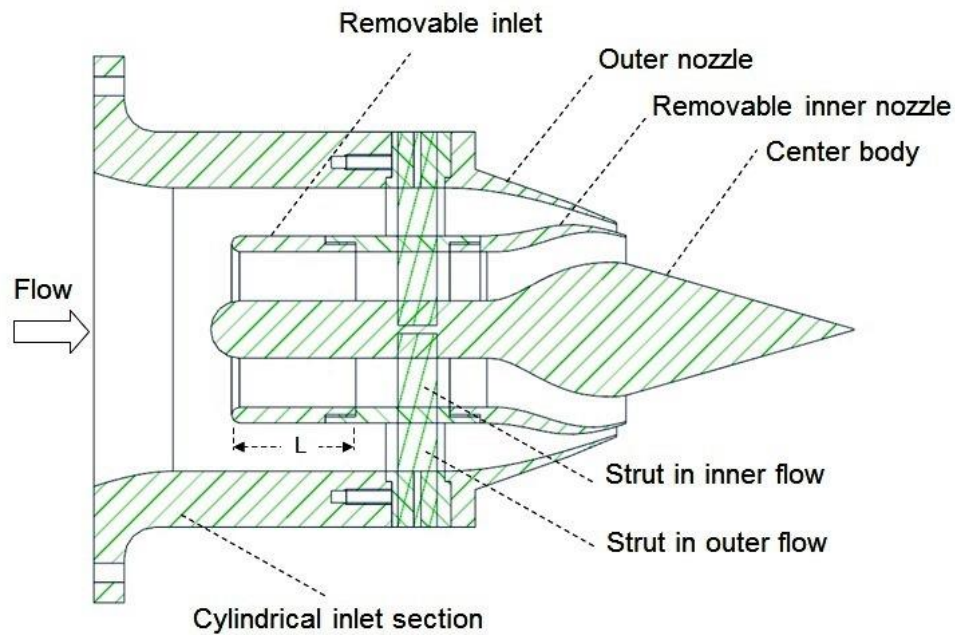
CVP42\_66630

Scenario 4: Lossless Conditions / 1ft Radius / ModelScale

polar = 90°

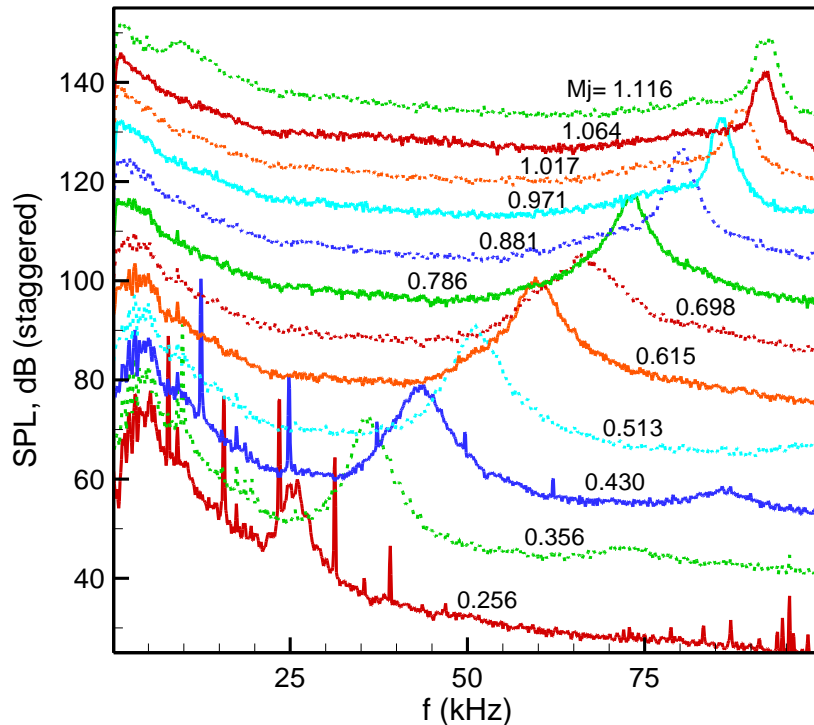


## 0.46-scale model of two-stream nozzle

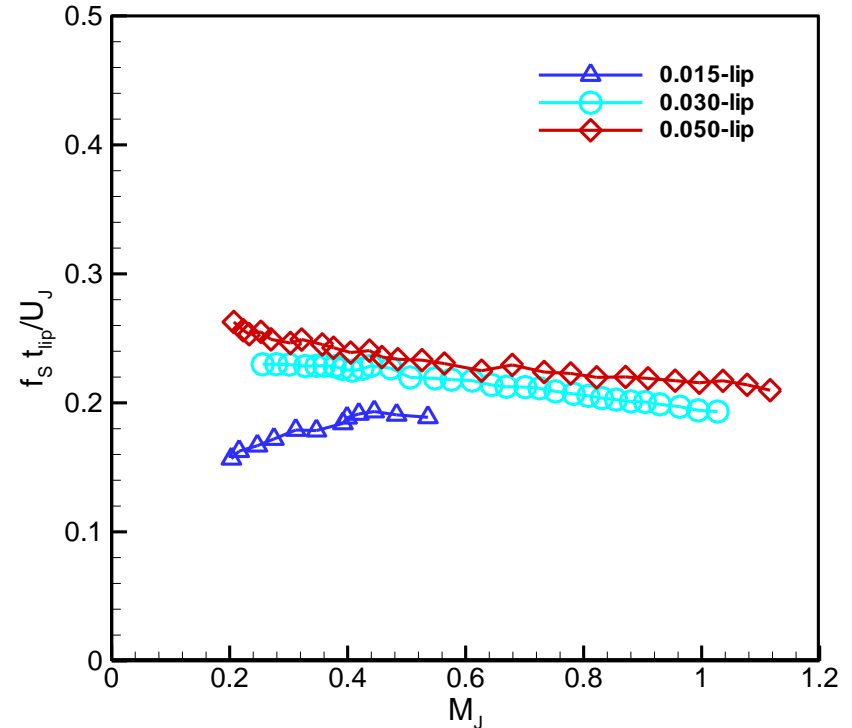


## Sound pressure level spectra ( $\theta=90^\circ$ )

0.030 lip case



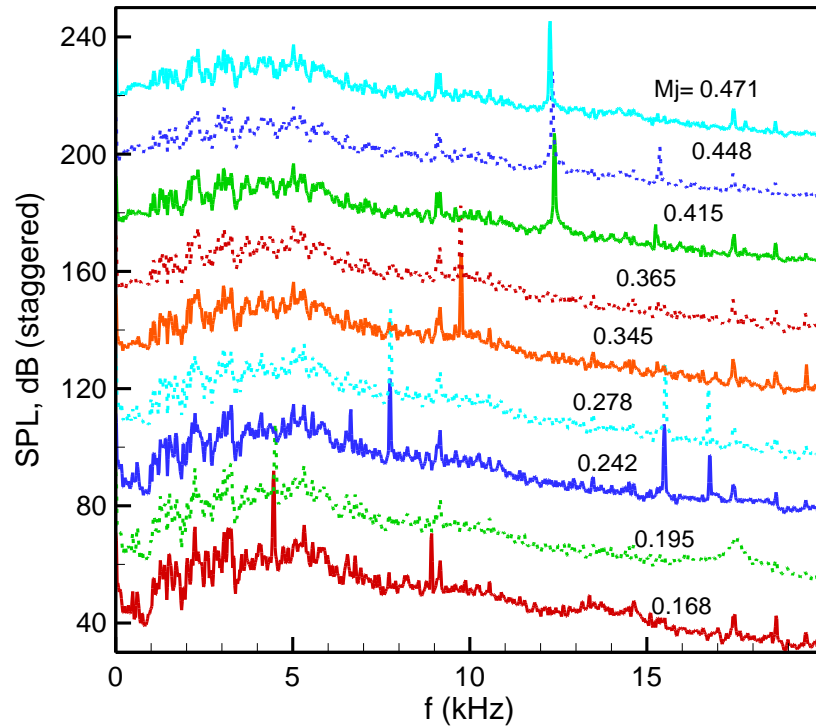
BB peak freq data for all three inner nozzles



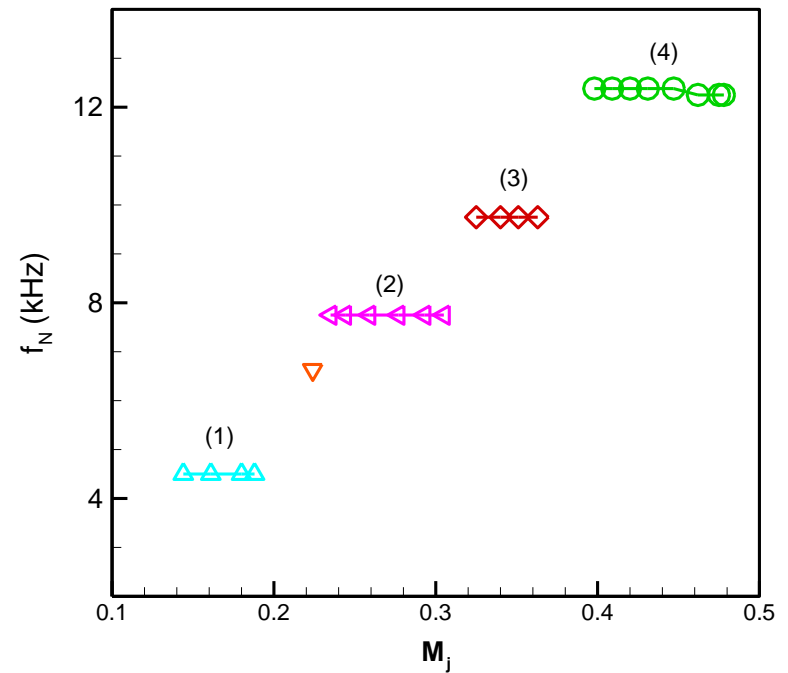
- Broadband peak is due to TE shedding (frequency of peak increases with  $M_j$ ); Strouhal number based on lip thickness is about 0.2.
- There are sharp tones at lower  $M_j$ .

## Sound pressure level spectra in low $M_j$ range

SPL spectra

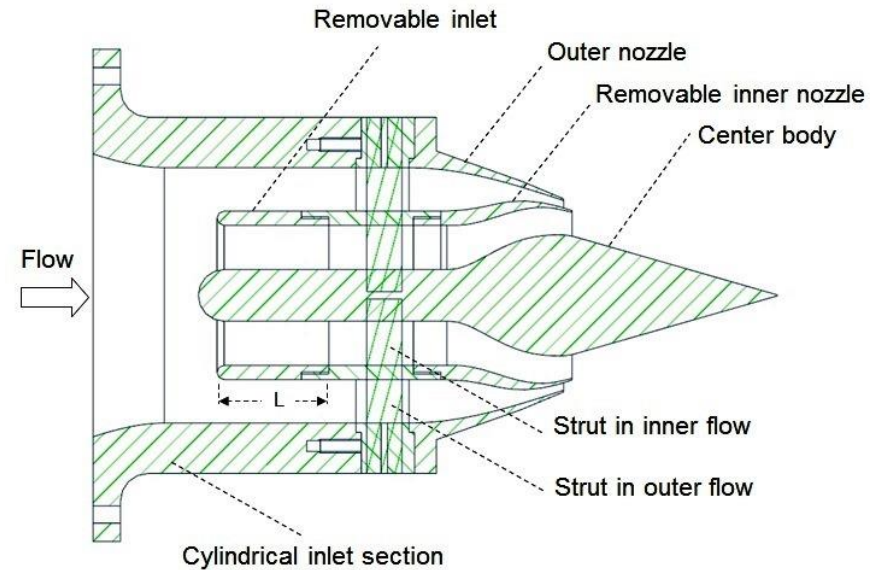
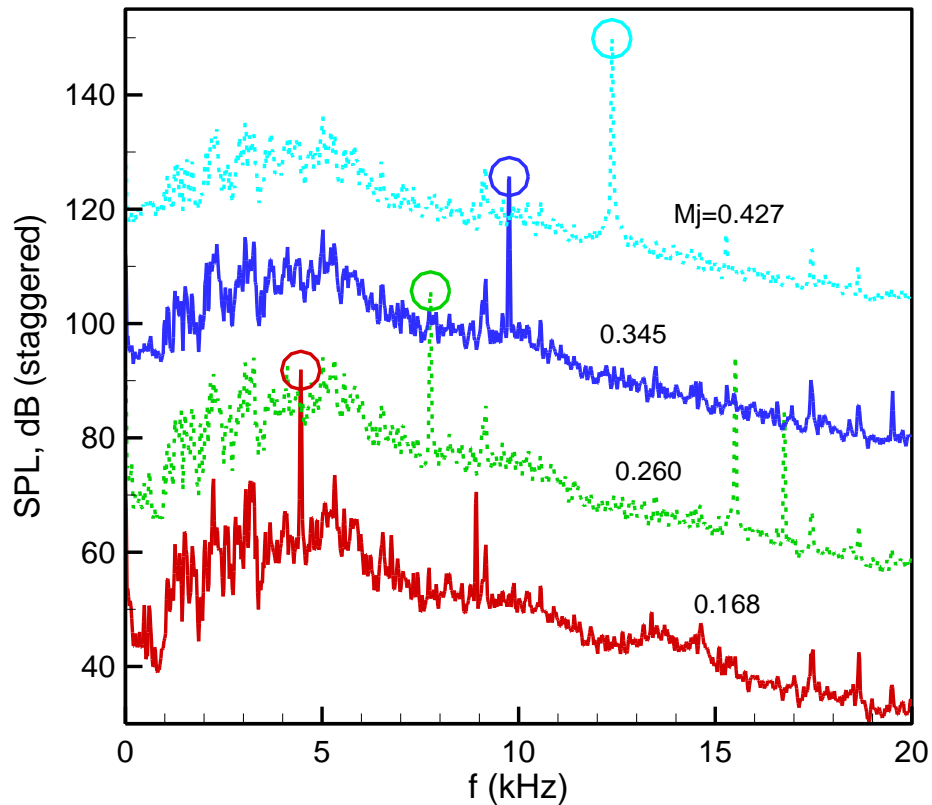


Frequency of dominant peak vs.  $M_j$



--Frequency of tone varies with  $M_j$  in steps.

## Four cases corresponding to the four stages are explored with parametric variation



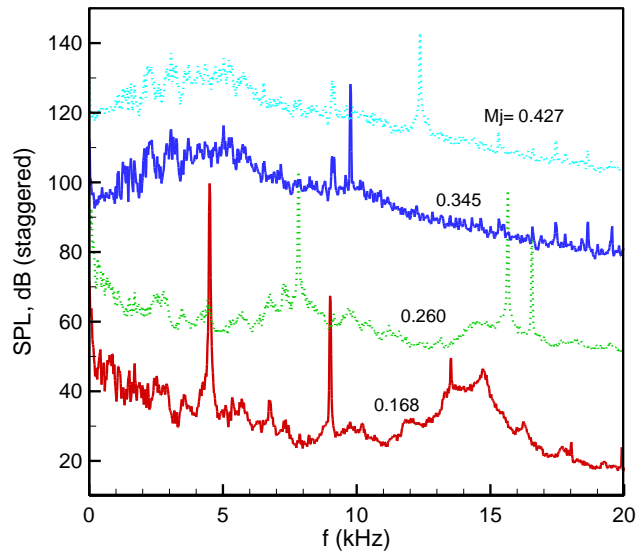
Parameters varied:

- Lip thickness of inner nozzle
- Inlet length ( $L = 0.75, 2, 4.75$ )
- Flared and constricted inlets
- Lip-to-lip distance

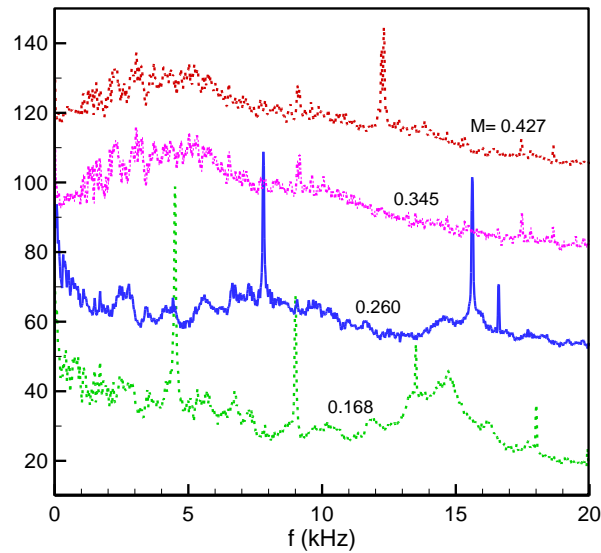
# Effect of changed lip-to-lip distance

## Changed by unscrewing inner nozzle

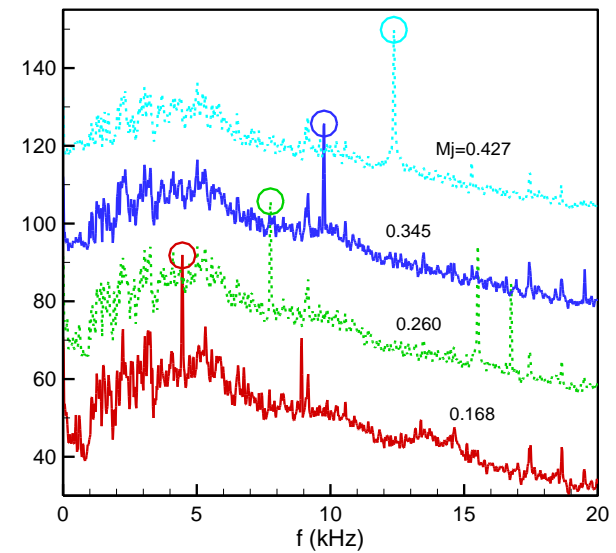
Gap = 0.16



Gap = 0.26

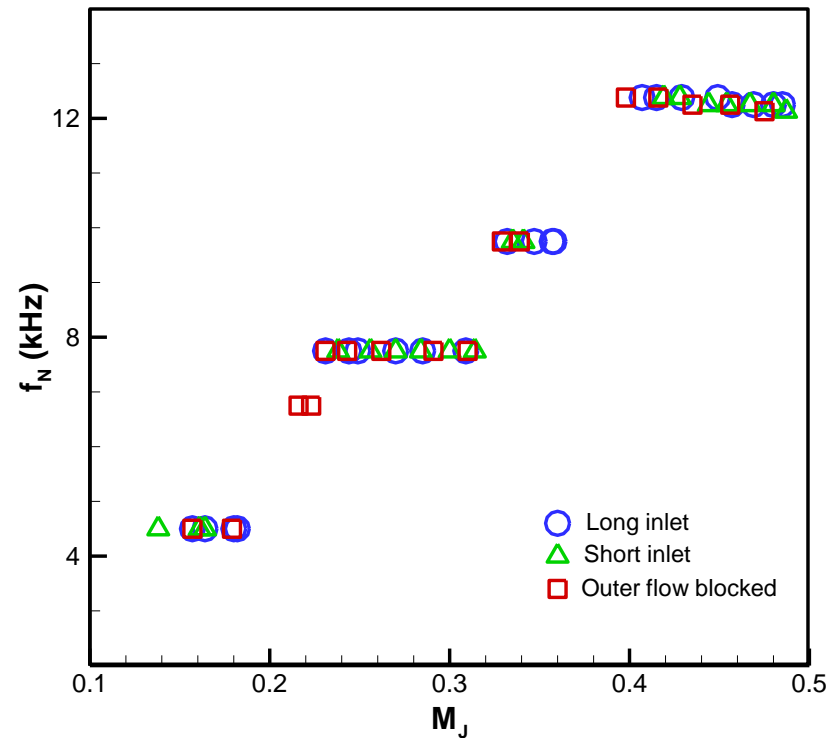


Gap = 0



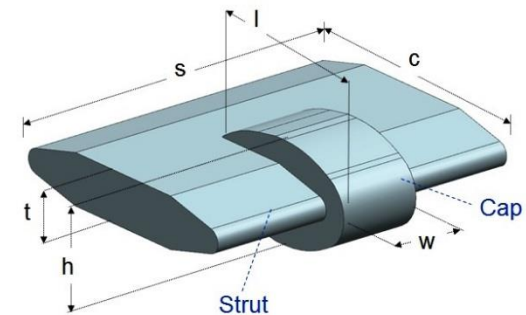
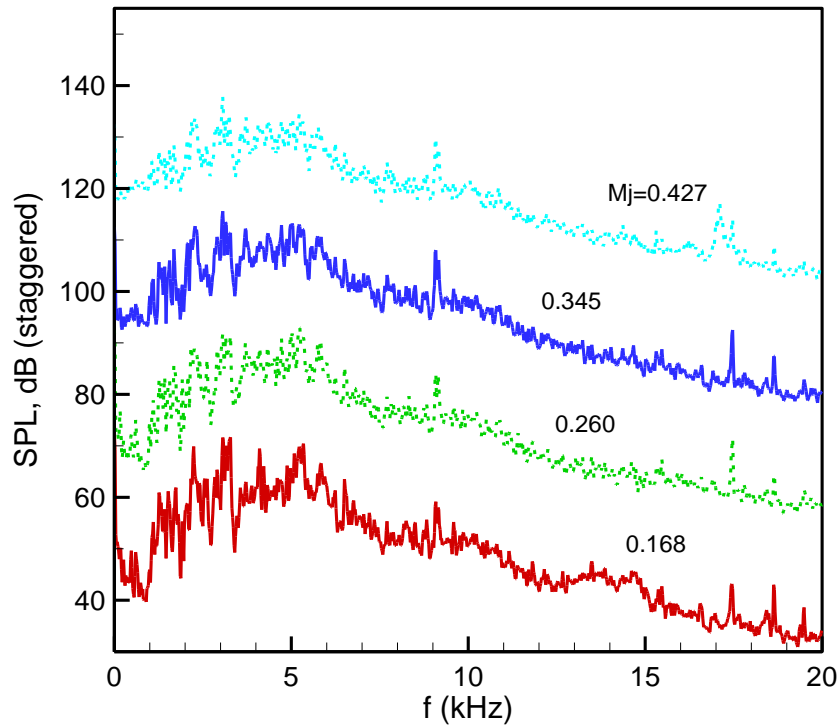
--Tone frequencies remained basically unchanged.

## Tone frequency vs. $M_j$ for different inlet lengths



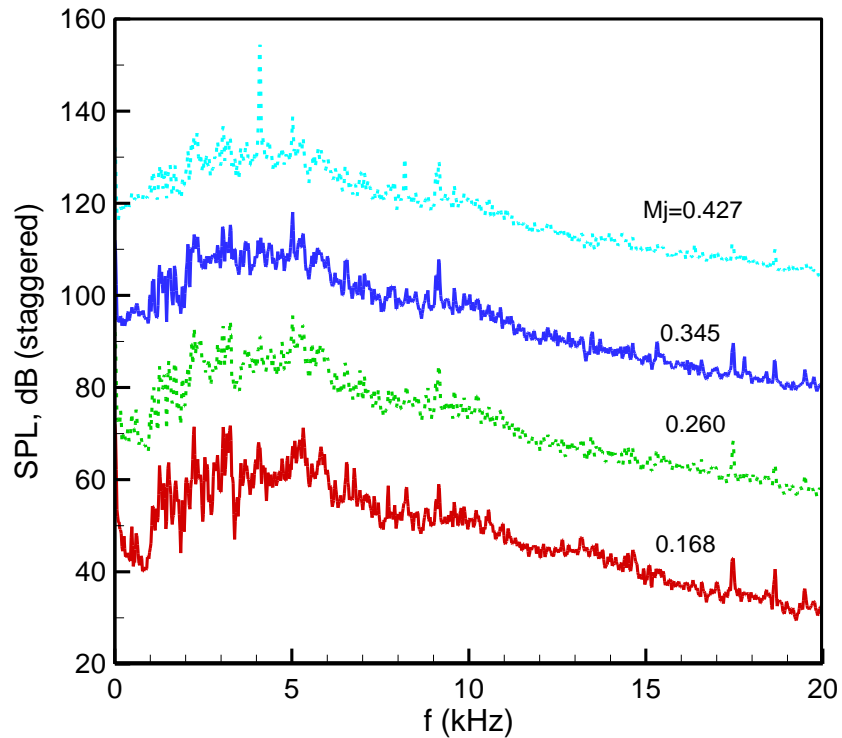
- With parameter variations noted in last slide frequencies were basically unaffected.
- Here data shown for inlet length variation and also with outer flow blocked.
- Same four stages occurred in all cases.

## SPL spectra with caps on inner struts



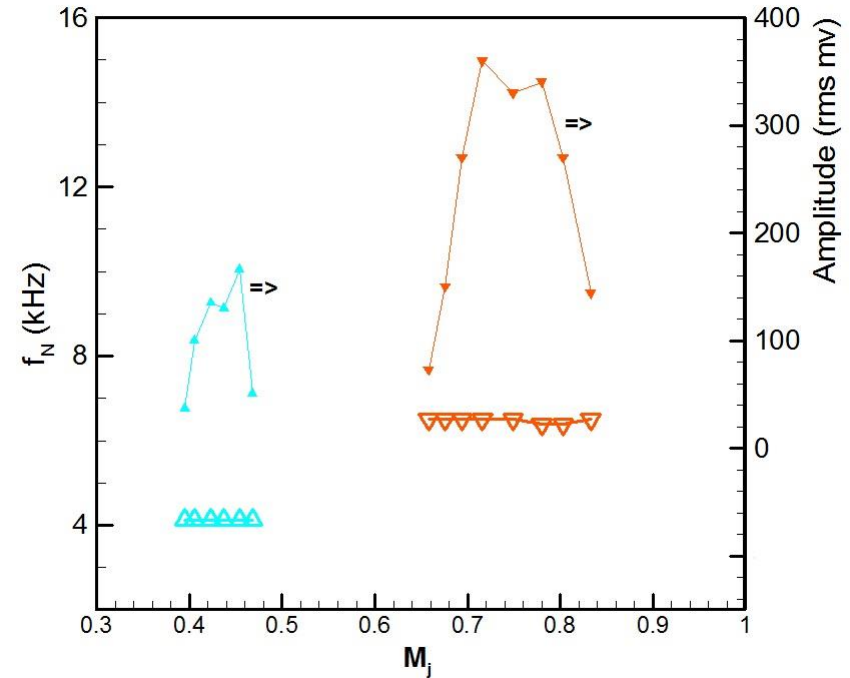
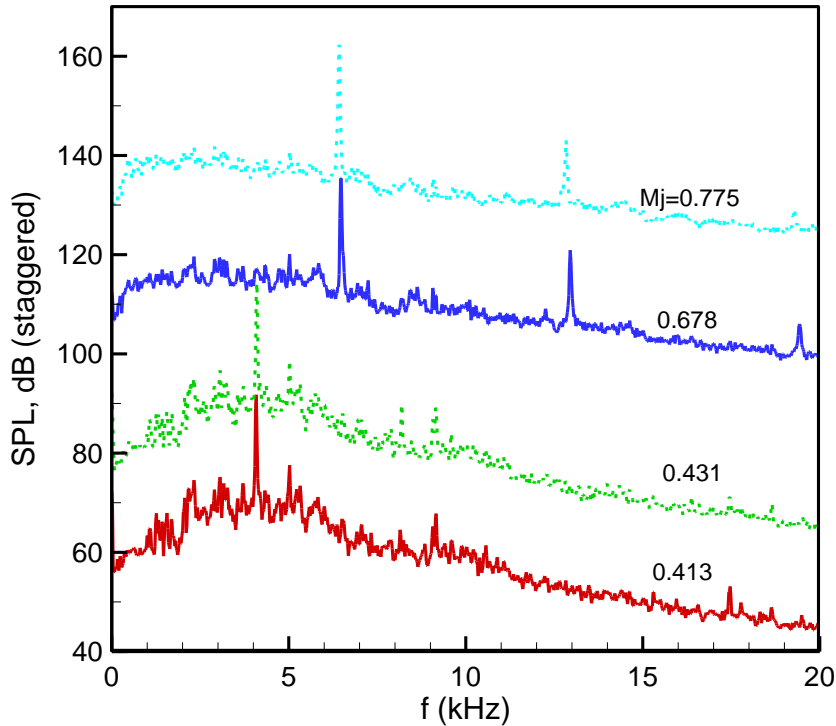
- caps with width  $w = 0.65$  (full span 0.8) took the tones out !!
- $w = 0.3$  or  $0.1$  were just as effective.

## SPL spectra with full-span caps on inner struts



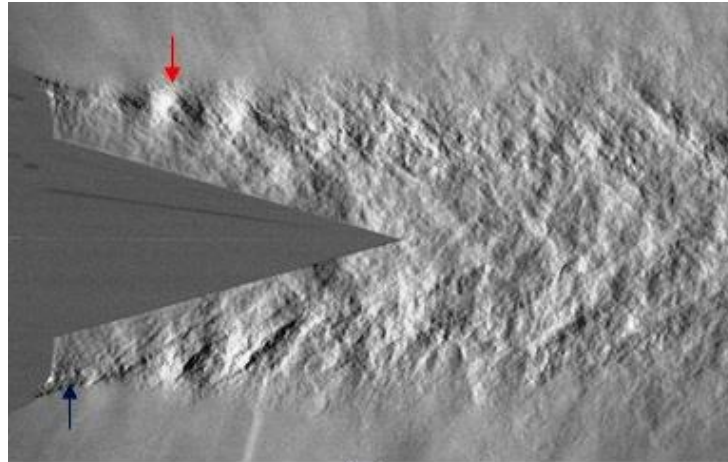
--Tones came back at higher  $M_j$ .

## SPL spectra with full-span caps on inner struts



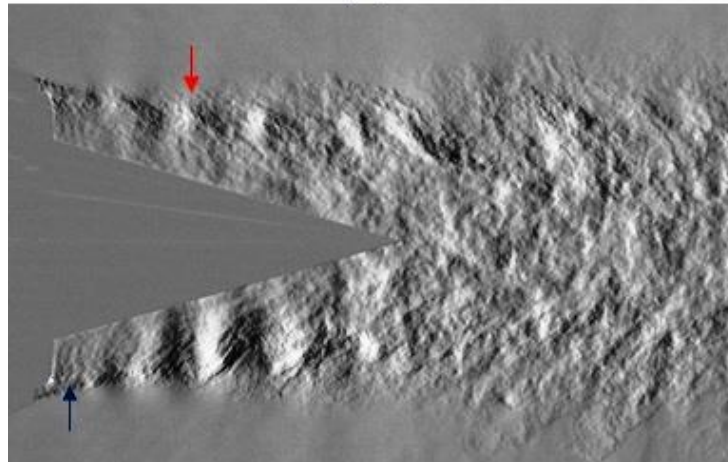
- Two stages of tones occurred in  $M_j$  range of 0.4–0.85.
- Amplitudes were the largest in the middle of each stage.

## Schlieren pictures of flow-field for full-caps on inner struts



(a)

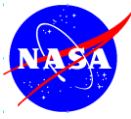
$M_j=0.45$ ,  $f=4.13$  kHz  
(shedding at 45 kHz)



(b)

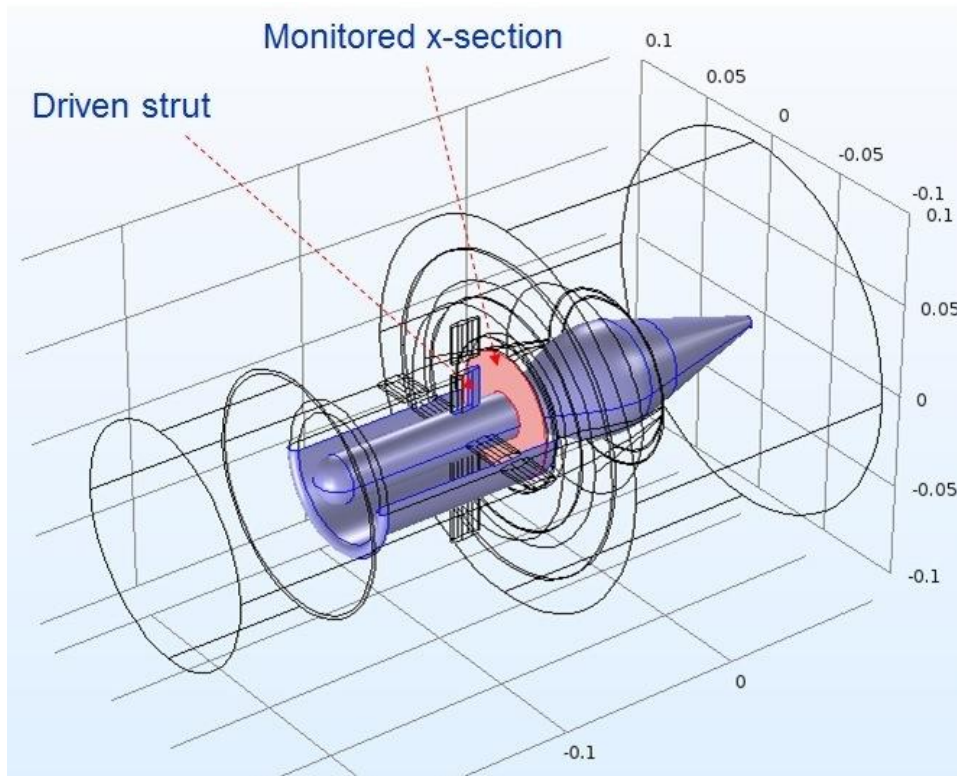
$M_j=0.67$ ,  $f=6$  kHz  
(shedding at 65 kHz)

- Tones excite the shear layer.
- Shedding from the inner nozzle lip can also be discerned upon inspection.



- Obviously, shedding from the struts couples with duct resonances to generate the tones.
- Experimental data did not shed any light on the nature of the duct modes.
- In order to study this, numerical simulation was done using a code, 'COMSOL Multiphysics', for the given geometry of the nozzle and struts.

## Numerical simulation



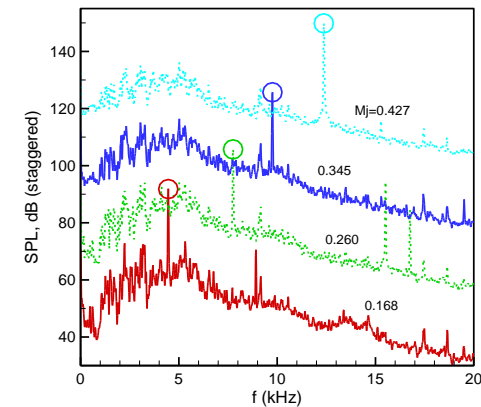
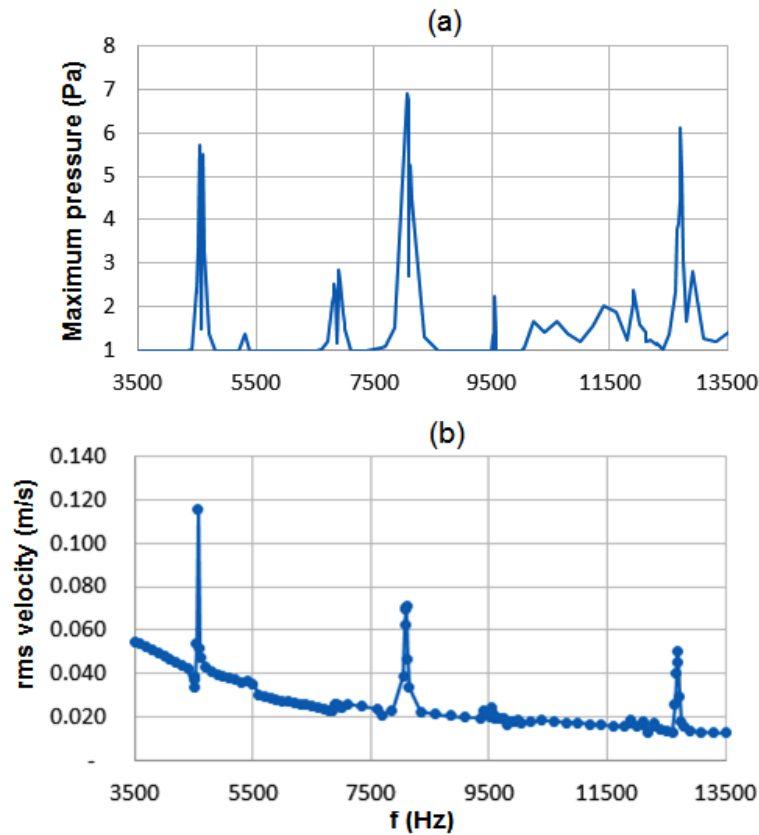
-- No flow.

-- Asymmetric perturbation imparted near TE of one of the four struts.

-- Solves for acoustic pressure field within the domain.

-- With perturbation at a given frequency maximum pressure and maximum velocity in the domain are monitored. This way a spectrum of the Response function is constructed.

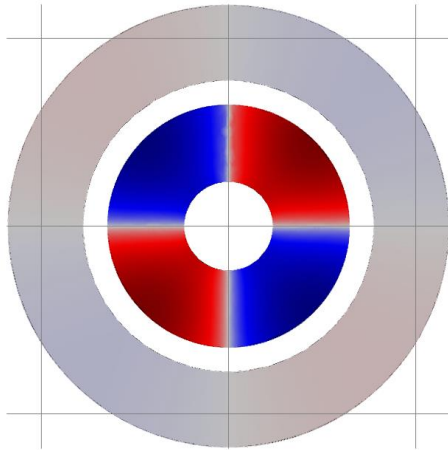
## Numerical simulation



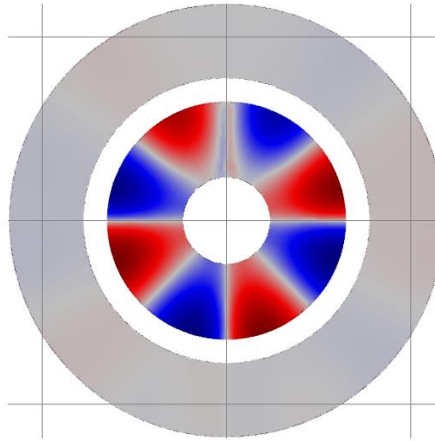
| $M_j$ | f (Hz)<br>experiment | f (Hz)<br>simulation |
|-------|----------------------|----------------------|
| 0.168 | 4460                 | 4565                 |
| 0.260 | 7760                 | 8054                 |
| 0.427 | 12375                | 12522                |

- Peaks at 4.46, 7.76 and 12.37 kHz are captured reasonably well !
- Peak at 9.76 kHz is not but there is a hint of energy around that frequency.

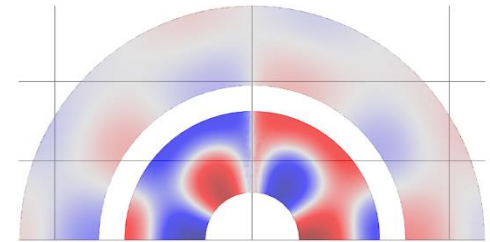
## 'Mode shapes' at monitored plane just downstream of struts



4.53 kHz



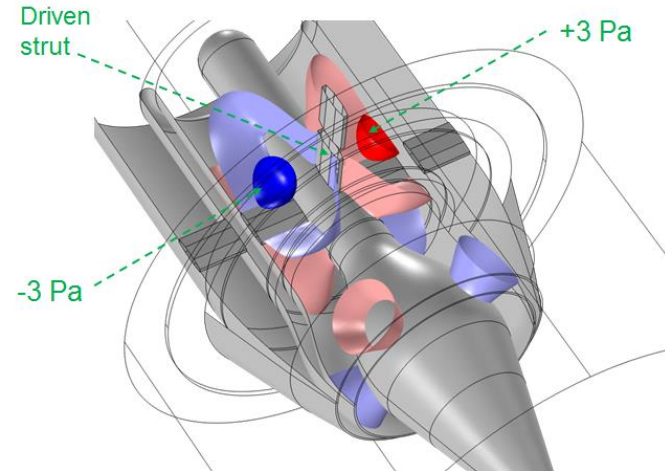
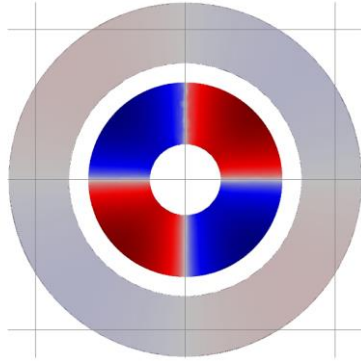
8.05 kHz



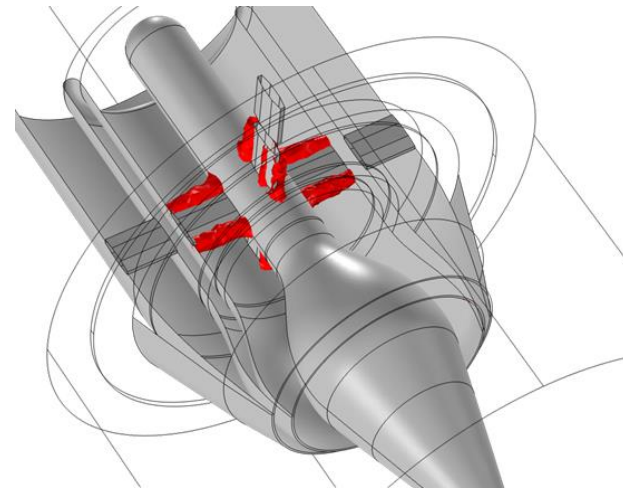
12.52 kHz

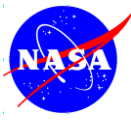
- 'Fundamental' involves positive and negative pressure regions in alternate intra-strut spaces, at a given instant.
- First harmonic involves pairs of positive and negative pressure regions within a intra-strut space.
- 12.52 kHz involves a complex azimuthal/radial distribution.

## Pressure and velocity distribution for fundamental (4.525 kHz) in entire domain



- Complex standing waves are set up around the struts.
- High pressure regions (anti-nodes) occur against the duct inner wall in between pairs of struts.
- Even though only one strut is driven, synchronized motion occurs from all four struts.
- Struts themselves are regions of velocity anti-nodes.

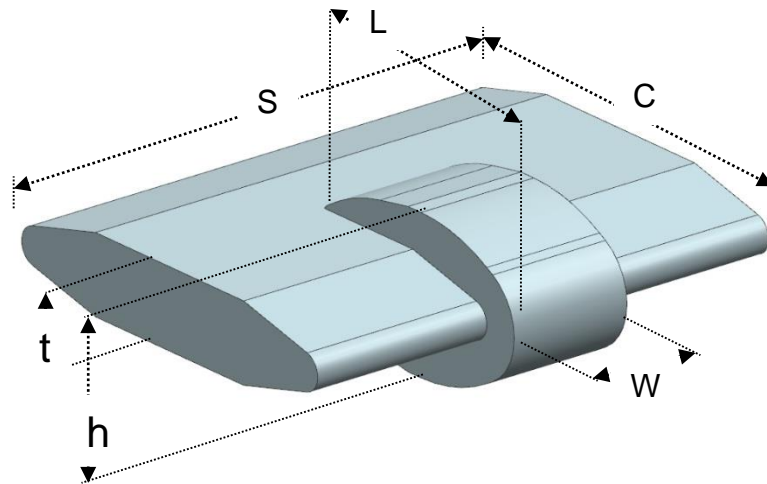




## Conclusions:

- The source of the tones is traced to vortex shedding from the struts.
- Perturbation from shedding couples with acoustic modes of the nozzle/strut, leading to step-like variation of tone frequency with Mach number.
- Standing waves form around struts. The fundamental involves alternating positive and negative pressure regions in intra-strut spaces. The pattern is anti-symmetric about a diametral plane. With increasing frequency the shape of the standing wave become more complex.
- A leading edge treatment of the struts in the inner nozzle eliminates the tones. This is due to a disruption of two-dimensionality of the flow that in turn disrupts organized vortex shedding.
- It is possible a similar remedy may work in other situations, e.g., in wind-tunnel tests where tones are generated by coupling of vortex shedding from some component with tunnel acoustic modes.

## Strouhal number based on local velocity and strut thickness



$$\begin{aligned} t &= 0.125 \\ c &= 0.65 \\ h &= 0.265 \end{aligned}$$

Straight inlet  
**No cap**

| $M_j$ | $f$ (kHz) | $ft/U_{in}$ |
|-------|-----------|-------------|
| 0.168 | 4.5       | 0.30        |
| 0.260 | 7.75      | 0.33        |
| 0.345 | 9.5       | 0.31        |
| 0.427 | 12.38     | 0.32        |

Straight inlet  
**Full caps on 4 inner struts**

| $M_j$ | $f$ (kHz) | $fh/U_{in}$ |
|-------|-----------|-------------|
| 0.45  | 4.13      | 0.22        |
| 0.75  | 6.45      | 0.21        |

- Shedding Strouhal number depends somewhat on geometry of strut
- It is apparent Karman shedding is the instigator for the observed tones